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THE EFFECT OF A CONSTANT VISUAL ANGLE UPON THE BINOCULAR DISCRIMINATION OF DEPTH DIFFERENCES

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THE EFFECT OF A CONSTANT VISUAL ANGLE UPON THE BINOCULAR DISCRIMINATION OF DEPTH DIFFERENCES

By Lloyd S. Woodburne, University of Michigan

If we set up two pencils a little distance away and close first one eye and then the other, the perceived distance between the pencils will not be the same. This illustrates *parallactic difference* or *binocular parallax*. Other terms which have about the same meaning are *binocular disparity* and *stereoscopic acuity*. In the following pages the term *visual angle* has been reserved for the size of the retinal image.

History of the Problem. Although the physiology of binocular vision has had a long history, and the acuity of binocular depth-discrimination has been carefully studied, little attention has been paid to the effect of the changes in size of the visual angle of the objects.

Pulfrich[1] (1899) was the first to take this factor into account. He repeated Helmholtz's pin-experiment, using, instead of pins, stereoscopic pictures. In this way he kept the size of the retinal image of the objects constant. He determined that normal eyes could discriminate differences in depth when the parallactic difference between two objects was as low as 10″. Since Pulfrich gives little detail, one cannot be sure just what conditions did exist, and, therefore no definite conclusion can be drawn from his investigation.

Heine[2] (1900) used three rods as test-objects, their ends covered by a diaphragm. The middle rod alone was displaced, the outside rods remaining 5 meters from *S*. *Ss* with normal visual acuity were able to obtain a limen as low as 12″ in parallactic difference between the two objects; while those having sharp vision could still discriminate at 6″. Heine seems unaware of Pulfrich's problem.

Bourdon[3] (1900) made a careful study of stereoscopic acuity. He constructed a much more delicate apparatus which allowed the image of three pins to fall on the foveal region. The head was held firmly in position. When the stationary rods were two meters distant, he was able to appreciate a displacement of 1.5 mm. This is equal to a parallactic difference of 5″, which Bourdon found was the smallest value that he could obtain by the vernier method in monocular acuity. Bourdon does not mention the possibility of changes such as those in which we are interested.

* Accepted for publication December 12, 1932. The writer wishes to express his appreciation to Professor John F. Shepard, under whose guidance the investigation was carried out; also to Professors Burton D. Thuma and Carl R. Brown, for suggestions and criticism.

[1] C. Pulfrich, Über den von der Firma Carl Zeiss in Jena hergestellten stereoscopischen Entfernungsmesser, *Phys. Zsch.*, 1, 1899, 98.

[2] L. Heine, Sehschärfe und Tiefenwahrnehmung, *Arch. f. Ophthal.*, 51, 1900, 146. 51, 1900, 146.

[3] B. Bourdon, *La pèrception visuelle de l'espace,* 1902, 1-442.

The next important work was done (1919) by Howard.[4] He used only two rods, the ends covered and both movable, so that there was no constant point of orientation. The rods were placed at 6 meters and separated 6 cm. from each other. The images of both fell on the fovea. Using a questionable method, he found a 75% limen as low as 1.8″ for a few of his best *Ss*. These results were obtained only with *Ss* of high visual acuity and perfect balance of eye-muscles. He failed to take into account our factor of size of angle.

Andersen and Weymouth[5] (1923) redetermined the threshold of binocular depth-discrimination with normal vision. Threads were used as test-objects, the middle one movable. The threads were 2 meters from *S*, and were exposed for 1.5 sec. The 2-meter distance was alleged to reduce accommodation to a minimum. Since the movement of the middle thread is limited to 6 mm., the change in its apparent diameter was said to be too slight to be used as a cue. This latter claim is not substantiated. The limina lie at the points where the 50%-line crosses the curves of the distribution of the near- and the far-judgments; *i.e.* the 50%-line indicates the position where judgments of near and far equal half the total number of judgments at any position. This range from the point of 50% far- to 50% near-judgments was then divided by two in order to get the average single displacement. The authors who averaged their interpupillary distance before they derived any individual values. While there is no objection to deriving average values, this should be done after the final individual values have been calculated. They have assumed in their calculations, by dividing the above range by two, that the curves of the far- and near-judgments are identical in character and slope. As will be pointed out later in this article, this is not necessarily true; nor is there any constant relationship between the subjective and the instrumental zero. The curves are drawn from the summed results of all thread-lengths in each series. Their results on a thread-length of 2 cm. in series B have been used for comparison with our own. They were plotted and the values calculated in a manner identical with ours. The value obtained in this way is a j. n.d. of 2.08″ or a distance of 0.152 μ on the retina.

Langlands'[6] (1929) test-objects were a maltese cross, a square, and a circle. These objects were placed before and behind the plane of a ship's mast and funnels which served as the plane of reference. *L*'s method of deriving his 50%-threshold was the same as Howard's and is subject to the same criticism, for the correctness of the reports has definite reference to the instrumental zero. By the use of lighted circular tubes and an exposure of 4 sec. *L* obtained a liminal value of 2.7″ parallactic difference. He finds that binocular resolution increases with the intensity of the illumination and with interpupillary displacement. From this fact he infers that the size of the retinal image, the effect of diffusion-circles, and the differences of perspective in direct and indirect vision are all negligible. He also attempted to control the factor of size of retinal image, but was unsuccessful in finding a mechanism which would keep the visual angle constant.

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[4] H. J. Howard, A test for judgment of distance, *Amer. J. Ophthal.*, 11, 1919, 656.
[5] E. E. Andersen and F. W. Weymouth, Visual perception and retinal mosaic, *Amer. J. Physiol.*, 64, 1923, 561.
[6] N. M. S. Langlands, Experiments on binocular vision, *Med. Res. Council, Privy Council,* Spec. Rep. Ser. No. 133, 1929.

The Problem

Thus far we have considered only those changes in the visual angle of an object which take place when the object recedes from or approaches the eye. A second change lies in the perspective effect. Thus parallel lines or objects seem, as they recede, to come closer together and this change also gives a cue to the distance of the object. The effect of these two sources of change is the chief problem of this investigation.

An accessory problem concerns the ability to discriminate depth-differences when the eyes are not fixated upon the median plane in the primary position. The question is simply one of relative torsion, assuming that torsion of the eyeball does really occur with change of position. The answer to this question should be instructive, since, if comparable values are found, they would indicate that this type of discrimination is not dependent upon any fixed alignment or arrangement of the retinal elements.

Apparatus

Andersen and Weymouth used a thread-length of 2 cm. They found empirically that this length gave the best results, but they did not vary the diameter of the thread. In a preliminary experiment I determined that slightly better results could be obtained with a thread-diameter of 0.3 mm. instead of the 0.5 mm. which they used. I then designed slits, to be illuminated from behind, that would have minimal dimensions of 2 cm. by 0.3 mm. and whose proportions would remain constant whatever the actual size. The slits were designed to eliminate the factor of visual angle in all the respects mentioned above. As the distance from *S* increased, the actual size of the slit also increased, so that the visual angle remained the same at all positions. In Fig. 1, which illustrates the exposure-slits in detail, the mechanism is shown for the automatic adjustment of the size of the slits. The heavy line A is the length of the slit that was illuminated. Its extent is from the overlapping flange above A to the cross-piece just below. The outside edges of each slit and the inside edges of each frame were milled to an angle of 26′ to allow for proportional changes of the slit-width as the height increased. Small springs extending between the two halves of each slit at the top and bottom held them firmly against the sides of the frame and insured the full width that corresponded with a particular height.

A wedge B is the means of pushing the slit A upward and so increasing the actual size. The movement of this wedge is controlled by that of the attached wheel C on the track D. This track was an inverted brass T-beam, whose distance from the tracks (G) on which the slits moved decreased the greater the distance from *S*. The rear end of this brass T-track was, then, 3 cm. higher than the front position, and consequently the slits were 3 cm. longer at that farthest position. At this rear position the brass T-track was hinged to allow adjustment of the slant when desired. Consequently the farther back the slits were pushed, the greater would be the size of the slit in both directions, because of the upward push of the wheel-wedge mechanism C-B rolling on the sloping track D. The sides of the slits were held firmly down on the wedge by the set of springs indicated by F. The position of the vernier attachment is at E. The

distance between the slits was 38 mm. when the absolute distance from *S* was 207 cm.

The effect of perspective was eliminated by having the tracks on which the slits moved diverge sufficiently, as they receded, to make the slits appear equidistant from each other whatever the position. *S*'s head was held in position by a mouthpiece calibrated in degrees to give accurate and quick adjustment of angular changes in the horizontal direction. The end of the mouthpiece was coated with sealing wax,

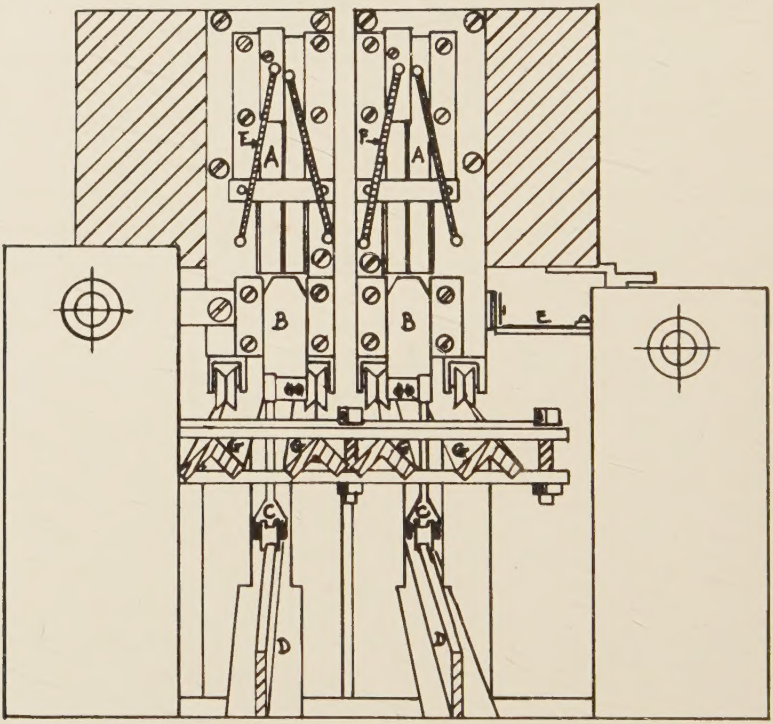

FIG. 1. DETAIL OF EXPOSURE SLITS

and *S* was told to bite into it while it was soft, making an impression of his teeth. This impression when hard held the head immovably. The mouthpiece was attached to a universal joint to allow adjustment in all directions and was clamped to an arm attached to the front support of the apparatus.

The light source was a neon tube behind each slit, the intensity of which was reduced and better diffusion obtained by gluing a piece of ground glass and two thicknesses of white paper just behind each slit. These neon tubes were coiled into a square and attached to a frame fitting into the tin boxes, to which the slits were attached. The electrical connections from the electrodes led out of the back of these tin boxes and thence either to the other box or to the transformer. The exposure apparatus was an adaptation of a Meumann time-sense apparatus to give contacts for illuminating the slits and warning signals at known intervals. The warning light allowed *S* to relax in the chair between exposures.

Although the experiment took place in a dark room *S* was kept light-adapted by a screen illuminated and tinted as nearly as possible the color and intensity of the slits. This was to avoid any possibility of a different light-adaptation for white and for colored lights. One *S*, who was practicing before the screen was tinted, reported that it was much easier to judge the depth-difference after the color was added. The intensity on this screen was controlled by means of a rheostat in series with the screen lights. A second screen of dull black finish was placed just in front of the slits to cut out any reflection from the tin boxes. Both screens had holes in them through which *S* examined the slits.

The readings were taken from a 3-meter steel tape calibrated in mm. and stretched from one end of the track to the other. The left slit was the one varied in position. It had a vernier attached which slid over the tape allowing for readings in either direction as fine as 0.1 mm.

Every effort was made to have everything except the apparatus comparable with the work of Andersen and Weymouth. The exposure-time was the same (1.5 sec.), as was also the statistical method. The factor of irradiation was virtually eliminated by altering the intensity of the light on the adaptation-screen. The interpupillary distance was measured by a mirror type of interpupillary distance-gauge, and each *S* was measured twice at different times by this method.

Method

A practice-period of 5–6 hrs. was given each *S*, in order to acquaint him with the process of judging depth-difference, and also to bring the practice-effect to a minimum. During this practice-period trials were made by the method of minimal changes away from and toward zero in either direction. Thus the general position of subjective zero was found and used as a point of reference for the placing of positive and negative intervals. After the practice-period the method used was that of constant stimuli, the first interval being some distance on either side of the subjective zero. Twenty-five readings were taken at each position, with the magnitude of the interval decreasing to zero. When *S* gave a majority of equal judgments, the interval was increased and 25 readings were taken at the same positions as before, but with an increasing size-interval. In this way the errors of habituation were counterbalanced. The order of presentation, arranged in advance, permitted 200 judgments without repetition.

The *S*s were instructed to record a + for a judgment of farther, = for indecision, and — for nearer. A maximum of 25 judgments was made at a sitting. (With 40 readings between rest-periods, the number of errors in the second 20 increased by as much as 50% over those of the first half.)

The exposure-timing apparatus was going continuously; and all changes of position were made in the dark with the aid of a flashlight. While these changes were being made a small hinged screen was flapped up in front of the second (black) screen to prevent the *S* from seeing the nature of the change.

The formula used for the derivation of the parallactic difference is that found in Helmholtz,[7] Hofmann,[8] and Howard.[9] It is: $p = 2a\delta/E^2$, where p = parallactic value in radians, 2a = interpupillary distance, δ = depth difference, and E = the mean

[7] H. Helmholtz, *Physiological Optics*, (J. P. C. Southall, trans.), 3, 1924, Note on Sec. 30 by Von Kries.
[8] F. B. Hofmann, *Physiologische Optik*, 1925, 418.
[9] H. J. Howard, *loc. cit.*

distance from the subject to the exposure slits. The derivation of this formula can be found in any of the references mentioned. It is understood, of course, that this formula holds only under certain conditions and is not always applicable. The conditions under which it can be used are: (1) the objects lie near the median plane of *S*, (2) the difference in distance between the objects is small, and (3) the distance from *S* to the objects is relatively great.

In order to change from a parallactic value in radians to one in angular seconds, the value in radians is multiplied by $180/\pi$, and that product in turn by 3600. Conversion from angular measure to linear distance on the retina is through multiplication of the tangent of the angle by the distance from the nodal point to the retina (15.5 mm.).

TABLE I

FREQUENCY OF THE THREE TYPES OF JUDGMENT AT THE VARIOUS INTERVALS

E.G.-VIII:SERIES A

Age: 38 I.P.D.: 64 mm.
V.A.: R 20/15 M.B. Exo-1½
L 20/15

Interval (mm.)	Judgments		
	near	equal	far
12		3	47
10	5	5	40
9	6	6	38
8	9	10	31
6	26	17	7
5	38	6	6
4	41	4	5
2	49	1	
Frequency Curve	Far limen:		.80″
	Near limen:		.67″
Parallactic Values			
Angular	Far limen:		2.23″
	Near limen:		2.03″
Linear	Far limen:		.167 μ
	Near limen:		.154 μ

It was decided to use the graphic statistical method of drawing a smooth curve through the points representing the frequency of a certain type of judgment. The point of crossing of the near- and far-curves was taken as the null position or the subjective zero. The limen was defined as the 50% point on the near- and far-curves. This point was derived by averaging the intervals corresponding to the 50%-point, the 75%-point, and the 25%-point. The figure (interval) represented by this average value was then computed from the null position to get the liminal value. In some cases the value of the mean of the judgments, as represented by the value T in the formula for the normal curve, was found. It showed, however, considerable variation and was not calculated for all cases. Several reasons for the use of the frequency-curve instead of the calculated mean are evident. In the first place, the central tendency of the judgments was what was desired, since the absolute numerical values were of no significance. The values derived were to be used only in comparison with the results under similar conditions when the size of the retinal image was not con-

trolled. We have taken a table on a thread-length of 2 cm. from the results of Andersen and Weymouth, and placed it with series A, as the most comparable with our own results. A more cogent reason for not using the calculated mean value is the fact that the individual curves show no regular progression, which is required for the use of such methods. In the sample curve which follows it is

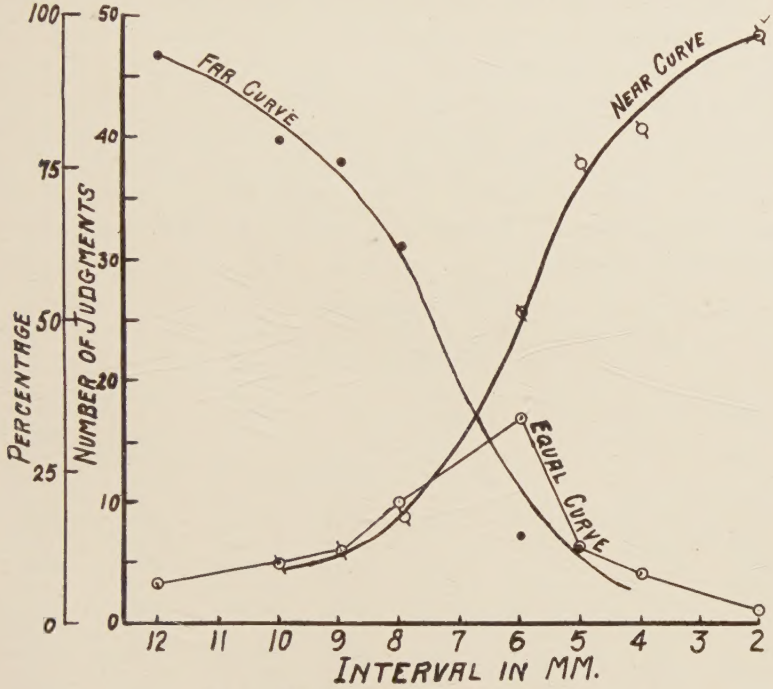

FIG. 2. CURVES OF E.G.-VIII, SERIES A

Far Limen = 0.8 mm.; Near limen = 0.67 mm.; Null position = 6.8 mm.

noteworthy that the tails of the curves, which express a low frequency of that type of judgment, do not come down immediately to the base line after passing the null position. This is indicative of a certain amount of oscillation of judgment, and is partly due, I am sure, to the attitude of *S* just prior to the exposure. If *S* is anticipating a far-judgment, the object will look far, and the converse likewise, no matter what the relative position of the slits. More than this, there is a certain amount of natural fluctuation which has been found to occur when small differences were under consideration.

A sample table and the curve which was derived from it are reproduced. Table I gives the frequency of the three types of judgments at the various intervals. The curve (Fig. 2) is merely a graphic representation of this same frequency, with the interval plotted against the frequency of a certain kind of judgment. Individual tables and curves were made out for each *S* and for each series. Then these individual values were averaged in the summary-tables which are given here.

In the tables, I.P.D. = interpupillary distance, V.A. = visual acuity, F = far-limen, and N = near-limen, M.B. = muscle balance.

Results

Series A. The slits were placed 207 cm. from *S*. Fifty readings were taken at each of 8 positions with the eyes in the primary position. The results of each *S* have been plotted in a curve for each series, and thereafter and only thereafter have summary tables been made out. It is not necessary to give all the individual tables and curves, since the sample given above illustrates very well all the factors which we shall discuss.

Below is given the summary of this series, with a summary of the results of Andersen and Weymouth on a thread-length of 2 cm. (Series B of their investigation).

TABLE II

Summary of Series A

Subject	No.	Age	I.P.D. (mm.)	V.A.	Limen (mm.)	Parallactic value angular	Parallactic value linear
K.D.	I	20	64.5	20/15	F: .59	1.82″	.136μ
				20/15	N: .47	1.45″	.110μ
S.E.	III	19	58	20/15	F: .64	1.81″	.135μ
				20/15	N: .66	1.83″	.139μ
F.R.	V	20	64	20/15	F: .56	1.72″	.129μ
				20/15	N: .40	1.23″	.092μ
V.G.	VI	18	61	20/15	F: .50	1.46″	.110μ
				20/15	N: .60	1.75″	.131μ
J.M.	VII	20	70	20/30	F: .73	2.42″	.183μ
				20/30	N: .57	1.91″	.144μ
E.G.	VIII	38	64	20/15	F: .80	2.23″	.167μ
				20/15	N: .67	2.05″	.154μ
H.W.	X	43	64	20/15	F: 1.03	3.21″	.242μ
				20/15	N: 1.50	4.10″	.340μ
					Av.:	2.12″	.159μ
Andersen and Weymouth:							
Series B			64 mm.	20/15	F: .67	2.16″	.162μ
(Length of thread: 2 cm.				20/15	N: .617	2.00″	.150μ
Separation of threads: 4 cm.)					Av.:	2.08″	.156μ

From Table II it can be seen that the average results of the group of seven *S*s was 2.12″ or 0.159 μ. There is a certain amount of variability in the individual results which does not show in the average. The averaging of the individual results is possible when these values are given in terms of angular seconds, since, at that stage, all individual differences have been already taken into account.

By reference to Table II it can be seen that the average of the results

of Andersen and Weymouth give a value of 2.08″ or 0.156 μ distance on the retina. The difference in magnitude between our results and theirs is sufficiently small to be ignored when the exactness of the two methods is taken into account. One would expect to find some difference between the two sets of results on the basis of the difference in apparatus and technique. We have, however, very definitely found values of the same general magnitude, and can draw comparisons quite adequately and justifiably. We may say, then, that, from the above comparison of results found when the visual angle was and was not under control, such changes are not a necessary cue to fine depth-discrimination; but when present they are likely used as an accessory means.

Series B-1. This is the control-group for the observations with the eyes in secondary positions. There were eight *S*s, each of whom gave 50 judgments at each of the 8 positions. Since this was a new group of *S*s, a five-hour practice-period preceded the recording of the judgments. The distance from the *S* to the slits was, in this case, 414 cm.

TABLE III

SUMMARY OF SERIES B-1

Subject	No.	Age	I.P.D. (mm.)	V.A.	Limen (mm.)	Parallactic values angular	Parallactic values linear
M.K.	XI	22	60	20/20	F: 2.8	2.1″	.158μ
				20/20	N: 2.8	2.1″	.158μ
J.M.	XII	20	60	20/20	F: 2.5	1.81″	.136μ
				20/20	N: 2.9	2.13″	.160μ
M.E.	XIII	20	62	20/30	F: 3.7	2.78″	.208μ
				20/30	N: 2.9	2.13″	.160μ
H.H.	XIV	21	63	20/15	F: 3.6	2.72″	.204μ
				20/15	N: 4.3	3.23″	.242μ
R.P.	XV	24	66	20/15	F: 1.1	0.87″	.065μ
				20/15	N: 1.0	0.80″	.060μ
E.H.	XVI	19	60	20/15	F: 1.6	1.16″	.087μ
				20/15	N: 2.4	1.73″	.130μ
E.K.	XVII	20	58	20/15	F: 4.5	3.12″	.234μ
				20/15	N: 3.1	2.16″	.162μ
					Av.:	2.11″	.158μ

Table III shows an average value of 2.11″, which corresponds to a retinal distance of 0.158 μ. These results are derived from the first seven *S*s. The eighth *S* was, on her own admission, discriminating on the basis of "real near" and "not so near." This indicates clearly that her range had not as yet been found at all. In Series B-2 and B-3 her range was discovered and small consistent results were obtained.

Series B-2. The same *S*s were used as in B-1; the slits were in the same

position as before, and the number of judgments continued at 50 per station.

There was, however, one important change which must be kept in mind. The mouthpiece, which held *S*'s head, was turned 15 degrees to one side or the other. Approximately half of the *S*s had their heads turned to the right and the rest to the left. This meant, of course, that the head turned about a point which was forward of the plane through the two nodal points. The axis of this rotation was 41 mm. When the head was in this position the eyes were turned back to look directly at the slits as before. If the head had been turned about a point directly under the center of the plane through the two nodal points, the eyes would have been turned exactly 15 degrees from the 'primary' position. Since this turning is done with the head at the end of a radius of 41 mm. we must calculate what is the actual turn of the eyes in order to face the slits as before. The radius of this distance moves the head to the side 1 cm., which causes a reduction in the angle of the eyes from the primary position of 8′. Thus the eyes now turn 14° 52′ instead of the full 15°. To find the decrease of the interpupillary distance which corresponds to such turning of the eyes we must take the cosine of 14° 52′ times the original interpupillary distance. The cosine of this angle is 0.9665. I have, however, used only the first two places of this figure in the following computations.

Since the time-allotment was short, it was impossible to give each *S* the length of practice-period that was desirable in this new situation. Consequently the number of mistakes in the early series of readings was probably larger than it would otherwise have been. The parallactic values derived show this when compared with Series B-3.

TABLE IV

Summary of Series B-2

Subject	No.	Age	I.P.D. (mm.)	V.A.	Limen (mm.)	Parallactic values angular	Parallactic values linear
M.E.	XIII	20	62	20/30	F: 4.6	3.28″	.246μ
				20/30	N: 3.8	2.70″	.208μ
H.H.	XIV	21	63	20/15	F: 4.7	3.39″	.254μ
				20/15	N: 4.4	3.14″	.234μ
R.P.	XV	24	66	20/15	F: 2.9	2.30″	.173μ
				20/15	N: 2.1	1.60″	.130μ
E.H.	XVI	19	60	20/15	F: 2.6	1.80″	.134μ
				20/15	N: 4.2	2.98″	.223μ
E K.	XVII	20	58	20/15	F: 4.5	3.00″	.224μ
				20/15	N: 4.2	2.80″	.210μ
F.L.	XVIII	17	61	20/20	F: 2.3	1.69″	.122μ
				20/20	N: 2.5	1.86″	.132μ
					Av.:	2.54″	.190μ

The figures in Table IV give the average result for 6 *S*s. This average was found better for purposes of comparison than the individual readings since there is a certain amount of variability which cannot be eradicated in the number of judgments used. In the computation of the average

values given for this series the results of M.K.-XI and J.M.-XII were not used. The reason in the case of M.K.-XI was that he consistently refused to give any equal judgments no matter how small the interval. It was learned in the case of J.M.-XII that after the first series a guess would be made one way or the other when it was impossible to tell the relative position.

TABLE V

SUMMARY OF SERIES B-3

Subject	No.	Age	I.P.D. (mm.)	V.A.	Limen (mm.)	Parallactic values	
						angular	linear
M.E.	XIII	20	62	20/30	F: 3.3	2.32″	.175 μ
				20/30	N: 4.1	2.90″	.217 μ
H.H.	XIV	21	63	20/15	F: 2.7	1.96″	.147 μ
				20/15	N: 2.3	1.67″	.124 μ
R.P.	XV	24	66	20/15	F: 1.7	1.30″	.097 μ
				20/15	N: 2.2	1.67″	.125 μ
E.H.	XVI	19	60	20/15	F: 1.8	1.25″	.095 μ
				20/15	N: 3.2	2.22″	.166 μ
F.L.	XVIII	17	61	20/20	F: 3.1	2.17″	.163 μ
				20/20	N: 3.0	2.11″	.158 μ
					Av.:	1.96″	.147 μ

We find that the average value for this series in angular seconds is 2.54″, which corresponds to the 0.190 μ linear distance to the retina. These values are slightly larger than those found for Series B-1. Some increase would be expected because of the lack of the full training period. Otherwise the figures should coincide, since the shortened interpupillary distance has already been taken into account in calculating the size of the parallactic angle.

The question which instantly arises is: Can the increase in the parallactic values be explained on the basis of lack of practice or is there some other factor to consider? A second possibility would be the factor of torsion, which is supposed to be present when the eyes are turned to the side. It is very clear that we have here a confusion due to the presence of two factors. Let us look for the answer to this question in the results of Series B-3, where we find merely the addition of a certain amount of torsion.

Series B-3. In this final series of our experiment we have the same situation found in B-2 with a slight addition.

The addition is the elevation by 15 degrees of the rear end of the apparatus. This, it is clear, increases the torsion considerably when the head is kept turned

15° to the side. The approximate amount of torsion of the eyes in this final position is equal to 1° 59′. An additional factor in this series is the fact that when the rear of the apparatus is elevated the absolute distance to the slits decreases slightly. The reason for this is that the mouthpiece is so situated that the eyes are 17 cm. above the front support of the apparatus and remain stationary in position. Thus the mouthpiece does not move when the apparatus is elevated, resulting in a slight decrease in distance from *S* to the slits. This decrease amounted to 4 cm., making the distance 410 cm. The difference in the parallactic angles due to this difference is almost negligible, amounting to 0.02″ or 0.00155 μ.

Here also the results of M.K.-XI and J.M.-XII were eliminated before the averages were calculated for the same reasons as stated in Series B-2. The subject E.K.-XVII did not finish this series and no results are included for him.

In this summary of this final series we have results which are slightly lower than those found in Series B-2. The average for B-2 was 2.41″, corresponding to 0.180 μ, while in B-3 we have obtained an average value of 2.30″ which corresponds to a linear distance on the retina of 0.173 μ. The decrease in the values for this last series is due, as we assume, to the loss from the lack of practice already mentioned in B-2. Since there is no increase in B-3 over B-2, we may safely conclude that in human adults any torsion that may be present does not reduce the fineness of binocular perception of depth differences.

Conclusions

As we have already suggested in the discussion of Series A, the values derived when the factor of the visual angle was kept constant are very little different from those calculated from the results of Andersen and Weymouth. These results are given at the end of the first series. The difference between our average value and theirs is 0.04″ or 0.003 μ. This is too small a value to be significant in a study of this sort. We may safely conclude, then, that normal changes in the visual angle of an object are not necessary cues in the binocular discrimination of depth-differences, although they are probably used as accessory cues when present. It would be expected that there would be some difference between the two sets of results due to the fact that in our investigation a different light-source and slightly different test-objects were used.

The comparison of the values derived from the three Series, B-1, B-2, and B-3, shows the relationship between the results with the eyes in the 'primary' position and those found when they were in 'secondary' positions. By reference to the summaries of these three series we can compare directly the results found under the various conditions. By means of such a comparison we find that in B-1, when the eyes were directed straight ahead, the average value of all subjects was 2.11″ which corresponds to a linear

distance on the retina of 0.158 μ. As has been already stated there was an insufficient practice-period before the readings were taken on B-2 with the eyes 15° to the side. The average values found for this series were 2.54″ or a retinal distance of 0.190 μ. This is an increase of 0.43″ and (0.032 μ) over B-1. As we have noted above, there is a confusion in the results of this series on account of the effect of the lack of practice and the possible effect of torsion in the eye-movement. In Series B-3 we have only an increase of this possible factor of torsion. The values for this last series, when the apparatus was elevated, are 1.96″ and 0.147 μ. If the results of the second series are compared with the last, it will be evident that there is a slight decrease in the values obtained. This decrease, which was found with a considerable increase in torsion (if real torsion does occur) would seem to show that the changing of the position of the eyes to this extent does not increase the limen more than would be expected on account of the decrease of the interpupillary distance. If there is real torsion of the eyeball in moving from one position to another, it does not affect the fineness of binocular depth-discrimination. It is evident, moreover, that there is no necessary relationship between this type of discrimination and any fixed alignment or arrangement of the retinal elements.

Supplementary Note. It will be noticed, if the reader turns to Table I and curve appended (Fig. 2), that there is a shift in the position of the equal judgments away from the instrumental zero. In 5 of the *S*s this shift was discovered, and in some cases to a considerable extent. When such a shift does occur it is impossible to use the correctness of the judgment as the basis for deriving the limen. Unfortunately this principle of correctness has been used by some of the experimental workers, notably Howard and Langlands, as mentioned above. It is, however, quite conceivable that the poor results recorded for Howard's *S*s, who had somewhat anomalous vision, might have been due to this reference to the instrumental zero. Such a method as he uses starts with an unproved assumption, instead of basing the derivation entirely upon *S*s' reports. A reasonable explana-

Subject	Shift	No.	V.A.	Muscle-balance
E.G.	backwards	VIII	20/15 20/15	Exo—1½, Hyperphoria—½ Abduction—6, Adduction—8
M.E.	forwards	XIII	20/30 20/30	Abduction—6 Adduction—0
E.H.	backwards	XVI	20/15 20/15	Eso—2, Abduction—6 Adduction—12.
H.H.	forwards	XIV	20/15 20/15	Accommod. Exo—2, Abduction—6 Adduction—10
F.L.	backwards	XVIII	20/20 20/20	O.K. O.K.

tion of such cases may be found in an examination of the refraction-records of those *S*s whose results show such a shift. The tabulation above gives in detail the visual acuities and the muscle-balance of these *S*s.

It will be promptly noted that there is very little asymmetry in the acuity of the two eyes. When we look at the muscle-balance of each subject we do find some discrepancy. It seems that in all but one case (F.L.) there is imbalance of the eye-muscles with a shift in either direction. We may suggest, then, that a lack of balance of the eye-muscles is often accompanied by such a shift in the position of equal judgments in front of or behind the instrumental zero.[10]

[10] It may be questioned how well the apparatus described above controlled the size of the visual angle. One *S*, whose results are not included in Series A, worked for 30 hours without being able to decrease the number of errors below 8 or 10 out of 20 readings, with a depth interval of 3 mm. When the work was practically done and he was asked what he had used as his basis of discrimination, he reported that he had tried to judge on the basis of the size of the slit. The nearer slit should be larger, he thought. It seems to the writer that this is a fair proof that *accurate* discrimination on the basis of the apparent size of the slit was impossible.